SYNC-VR: Synchronizing Your Senses to Conquer Motion Sickness for Enriching In-Vehicle Virtual Reality

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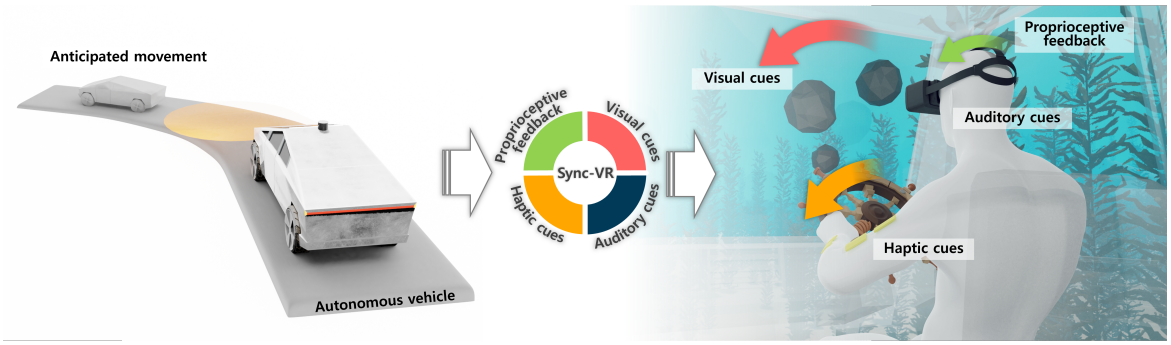

Figure 1: Adaptive tuning of the virtual reality experience by synchronizing sensory inputs to increase passenger presence and decrease motion sickness

ABSTRACT

Passengers can engage more in nondriving-related tasks owing to recent advancements in autonomous vehicles (AVs), making immersive tools such as virtual reality (VR) appealing; however, motion sickness (MS) remains a significant challenge. We present SYNC-VR, a system that aligns with visual, haptic, and auditory cues and provides proprioceptive feedback to illustrate its effect on MS and presence within the in-vehicle VR. We conducted an experiment with 24 participants using a real vehicle along a route with known MS-triggering events. Using subjective and physiological measures, we assessed participants' presence and MS under four conditions by gradually varying the level of synchronized input sensations. Results reveal that SYNC-VR reduces MS and increases the sense of presence. Additionally, it emphasizes the impact of our interactive VR content and its role in achieving proprioceptive feedback with haptic feedback through electrical muscle stimulation, introducing an innovative approach to MS mitigation in in-vehicle VR.

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CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction paradigms; Virtual reality.

KEYWORDS

autonomous vehicles, virtual reality, motion sickness, presence, visual cues, kinesthetic feedback, sensory alignment, haptic feedback

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1 INTRODUCTION

When traveling in autonomous vehicles (AVs), passengers engage in nondriving activities for entertainment or work [27] such as viewing digital content on smaller displays, including smartphones or tablets [28]. Most passengers experience motion sickness (MS) while reading a book or using a smartphone inside a moving vehicle [29] due to the discordance between their perceived visual input and the vestibular sensations within their body [30]. Virtual reality (VR) offers a compelling solution by creating a simulated world that can be accessed via specialized headsets, allowing passengers to engage with immersive and large-scale digital content and making travel time productive and highly enjoyable [31]. VR will allow passengers to engage in various activities including working on presentations, attending virtual meetings, accessing educational content, or simply enjoying entertainment options such movies, games, or virtual tours. The integration of VR technology with AVs presents a unique opportunity, transforming all current drivers into potential passengers who can benefit from VR applications. This shift aligns seamlessly with the evolving passenger experiences in AVs, enabling passengers to perform a wide range of activities from work to entertainment [1, 2].

While VR technology holds the potential to alleviate MS in a moving vehicle [33-35], it can also be a source of MS due to its inherent requirement to block any visual inputs from the real world [32]. This paradox arises from visual–vestibular mismatch, where the eyes perceive motion that contradicts signals from the balance sensors of the inner ear. Thus, digital content design and its impact on the interaction between sensory inputs provided by the VR content and those originating from the surrounding environment inside the vehicle must be considered for integrating VR in AVs, and the said mismatch must be addressed for creating comfortable VR experiences. Several in-vehicle movements trigger the visual–vestibular mismatch that stimulates MS when the passenger's vision is entirely occupied by the head-mounted display (HMD). MS can be caused by **turning** that uses a combination of acceleration, deceleration, and changes in visual field orientation [33, 36]; **inconsistent motion** such as sudden stops or starts; **vertical displacement** such as passing over a speed bump and undulations during a car ride and vertical oscillations resembling heaving [11, 12, 33]. Understanding and addressing these factors are crucial for designing better in-vehicle VR experiences.

Visually immersive VR content that aligns with physical vehicle motion can reduce visual–vestibular mismatch and MS. Hock et al. addressed this challenge by integrating VR into moving vehicles, wherein vehicular movements were synchronized with visual cues [10, 43]. Visual cues in an underwater environment were also explored [6], wherein fishes moved in the same direction as the vehicle.

These advancements pose an inquiry: can visual cues enhance the presence and mitigate MS for all applicable real-world driving scenarios? Real-world driving experiences are complex and involve many sensory inputs besides visual cues such as vestibular cues, the body's sense of balance and motion (e.g., the feeling of being pushed back into the seat during acceleration or leaning to one side during a turn); haptic cues, sense of touch (e.g., the vibrations and jolts through passengers' seats and bodies when driving on a bumpy road); proprioceptive feedback, the body's awareness of its own position and movement (e.g., bracing against the seat during sudden braking); auditory cues, sounds experienced during driving (e.g., the sound of screeching tires of rapid deceleration). Factors such as unexpected jolts, vertical displacement, and varying acceleration patterns challenge the effectiveness of visual matching. Therefore, the dynamics of sensory integration [13] and sensory inputs, such as haptic cues, proprioceptive feedback, and auditory cues, must be explored to mitigate MS in in-vehicle VR experiences.

Thus, we conducted a field experiment using an experimental electric vehicle as an on-road testbed. A specific route was selected to induce MS, incorporating turns, speed bumps, and areas that necessitate abrupt decelerations, stops, and accelerations. We recruited 24 participants who engaged in four distinct conditions that varied depending on the level of passenger's synchronized input sensations aligning with the actual vehicle movement. The participants' sensory inputs were sourced from four distinct origins. VR was first used to deliver visual and auditory digital content to the participants. Further, crafted virtual interaction scenarios were used to influence participants' engagement with the virtual environment (VE), thereby facilitating proprioceptive feedback and vestibular cues. Haptic feedback was introduced via electrical muscle stimulation (EMS). Lastly, other sensory inputs originated from the physical environment of the vehicle (e.g., vehicle motion and olfactory cues).

When passengers wear an HMD, their bodies feel various sensations caused by the vehicle movement. SYNC-VR (Figure 1) is used herein to elevate in-vehicle VR experience by harmonizing the participants' senses with the vehicle movement. SYNC-VR introduces interactive VR content that enriches passengers' engagement by influencing their perception of movement to mitigate the impact of in-vehicle dynamics on their senses. SYNC-VR uniquely uses EMS for obtaining haptic feedback and enhances passengers' presence level during travel. By aligning passengers' sensory inputs with the vehicle environment, MS can be effectively reduced and passenger presence can be enhanced. SYNC-VR introduces exciting possibilities for developing better in-vehicle VR experiences by marking a significant leap forward in travel entertainment and comfort.

By triangulating the collected data from multiple sources, including subjective participant feedback, physiological measurements, and qualitative interviews, we aimed to address the following research questions (RQs):

- RQ1: Does an exclusive reliance on visual cues adequately enhance presence and mitigate MS across a range of real-world driving events that trigger the most MS?
- RQ2: How do various sensory inputs, including proprioceptive feedback, visual cues, auditory cues, and haptic cues, interact to influence presence and MS in in-vehicle VR experiences?
- RQ3: How does the anticipation of on-road driving events, such as turns, vertical displacement, and irregular accelerations, influence the need for real-time adaptive tuning of VR

experience to improve passenger presence and decrease MS during AV travel?

2 RELATED WORK

2.1 In-vehicle VR Applications

The increasing use of AVs have enriched travel experiences [58], thereby increasing the demand for in-vehicle entertainment and work provisions. VR can potentially meet these demands. For instance, VR is used to enhance navigation and routing tasks by creating immersive experiences [1] and is used for testing and advancing AV technology [7, 8]. It is also employed to enhance passenger trust in AVs by providing them visual cues related to the vehicle's sensory and planning systems [9] and for productivity tasks such as reading during travel [35]. Beyond these applications, VR is also a versatile platform for investigating driving behavior and exploring novel concepts including gamification and personalized interfaces [3]. It plays a significant role in advancing safety research by simulating augmented reality (AR) awareness cues and enabling opportunities for AR and VR solutions in automotive safety studies [4]. Furthermore, VR transforms passenger experiences, including enhancing entertainment and productivity [5].

Although, VR holds promise for application in AVs, its use in moving vehicles is challenging, particularly because of potential conflicts between visual and physical sensations that cause discomfort or MS. These outcomes limit the use of VR in AVs. Additionally, while some of the previously mentioned studies have investigated the advantages of using VR in road vehicles, they encountered limitations in test routes, failing to consider driving routes that included events causing motion changes, such as turns, stops, and bumps. Our research focuses on developing a VR system that reacts to these MS-inducing events to resolve sensory conflicts and facilitate a more comfortable VR experience in AVs.

2.2 Presence and Immersion in In-Vehicle VR

The sense of presence is the feeling of being there in a VE and engaging psychologically and emotionally. It is influenced by the VE characteristics and user's perception [23, 75, 76]. Immersion, in contrast, uses the technical and design aspects of a VR system to enhance the sense of presence, including sensory fidelity and interactivity, and the system's ability to realistically mimic or represent reality [37, 74]. The sense of presence in a VE enhances with increasing immersion [13].

Several in-vehicle VR applications have been developed to enhance the users' level of engagement, with the ultimate objective to expand VR into vehicles and create immersive entertainment and workspaces that surpass the current limitations of a vehicle's physical interior [11, 35]. In-vehicle VR also enhances the overall VR experience by leveraging real-world characteristics, such as conveying a vehicle's motion consistently, from all viewing angles [10]. However, integration of dynamic and unpredictable physical motions into VEs without reducing immersion is challenging, which can be addressed by aligning vehicle movement with the corresponding VE to avoid sensory conflicts [11, 43]. Some studies, however, did not observe a significant enhancement in the sense of presence of participants despite their preferences for specific scenes that aligned with vehicle movement. By including supplementary sensory elements such sound, temperature adjustments, or haptic feedback, the realism and engagement of immersive experience can be enhanced [6].

Immersion can be enhanced by creation interactions in VR, such as using tracking technology, controllers, virtual hands, and avatars within a VE [38, 39]. Furthermore, haptic feedback can be integrated for enhancing user input interaction and elevating the overall immersion within the VR domain [40]. Multisensory cues and multimodal sensory feedback can also be incorporated in VR for enhancing immersive experience [40, 41]. Herein, multisensory cues are introduced in VR systems using multimodal sensory feedback to enhance the participants' overall perceived sense of presence and reduce MS.

2.3 Motion Sickness and In-Vehicle VR

MS refers to the discomfort, dizziness, nausea, and, in some cases, vomiting that individuals may experience when traveling in a moving vehicle. MS is primarily caused by a sensory conflict where the visual cues received by the eyes, such as the perception of motion from looking outside the vehicle, do not align with the signals detected by the inner ear, which helps maintain balance and orientation [1, 46].

MS is expected to be prevalent in AVs, where passengers will engage in nondriving activities such as work or entertainment during travel [27]. Consequently, the vehicle interiors will have to be redesigned to meet passenger needs such as obstructing the view of the external world [36] or expanding the potential for VR integration within vehicles to offer immersive entertainment and workspaces [8]. However, the motion displayed on the HMD worn by passengers may not match the vehicle's actual movement, particularly during turning [10] or inconsistent motion including sudden stops or starts, which can cause MS. Vertical movements, such as going over speed bumps or experiencing undulations during the car ride, can also induce MS [11, 12] due to the conflict between visual and vestibular signals [33].

Several approaches are employed to effectively reduce MS, such as using visual motion cues in VEs that offer supplementary information about the vehicle's motion [6, 49]. Conversely, other research has generated inconclusive findings, where no significant impact on MS was observed [48]. By matching the virtual motion with the vehicle's movement, the changing VE corresponds to the vestibular sensations and reduce MS [10, 34, 50]. However, these approaches emphasized that they did not reduce MS considerably [33, 34].

Some studies increased the sense of presence in VR applications by interacting with haptic feedback to reduce MS [51, 52]. In a study [53], researchers successfully helped users recover their in-vehicle VR presence after being interrupted by phone calls by developing an interactive armrest for providing haptic sensations. To increase the sense of presence, subjects were also asked to engage in various interactions during the VR experiment [39].

Passenger body posture within a vehicle, particularly during turning events, vertical displacement, and inconsistent vehicle movements, plays a significant role in MS due to the lack of alignment between the body and environmental changes [11, 54, 55]. Drivers experience less MS than passengers primarily because they

adapt their body posture in anticipation of upcoming events [16]. For instance, they tilt their heads toward the center of a curve when navigating a turn, whereas passengers tend to move their heads in the opposite direction. When passengers were instructed to emulate the driver's posture by tilting their heads toward the center of the curve, they reported a substantial decrease in MS [16, 56].

The concept of sensory alignment as a design dimension opens up numerous VR possibilities and exciting experiences [13, 57]. Herein, we introduce an approach to mitigate MS caused when using VR inside a moving vehicle. We build upon the concept of sensory alignment to establish a coherent connection between digitally induced and physically experienced sensory inputs of passengers. This strategy is distinct from Pöhlmann et al.'s study [49], who used audiovisual cues in a simulated motion environment with a rotating chair. This study used a real vehicle that experienced various real motion events such as turns, speed bumps, and abrupt stops, thereby offering a more comprehensive examination of MS triggers. While recognizing the foundational nature of Pöhlmann's work, Holoride's [72] and other similar research have focused on matching VR scenes with vehicle movements by relying primarily on visual and auditory cues, our study integrates proprioceptive feedback and haptic cues via EMS to elevate passengers' sense of presence and effectively combat MS within the context of an actual vehicular journey. SYNC-VR framework is designed that synchronizes the vehicle's motion with VE, integrates visual cues, and complements these with interactive inputs and haptic feedback. This framework is designed to assist passengers in anticipating upcoming vehicle movements [58], thereby fortifying their resilience against MS-inducing events.

3 EXPERIMENTAL DESIGN AND PROCEDURE

Herein, we investigate and address MS caused owing to using VR content in a moving vehicle. We do not assess or measure cyber sickness [79], which is a broader term encompassing the discomfort associated with various VR experiences, including those unrelated to vehicular motion. The relation between MS, user engagement, and the synchronization of various sensory inputs is investigated. When using VR digital content in a moving vehicle, specific senses are engaged through the virtual experience and the remaining senses continue to perceive and respond to stimuli provided by the physical environment. MS can, in part, be attributed to the misalignment or discrepancy between the sensory inputs originating from the digital system (VR) and those arising from the real-world surroundings (the moving vehicle). Thus, in addition to effective visual matching technique, we will examine the role of other sensory synchronizations in reducing the sensation of MS during real-world driving events, which are well-known triggers for this discomfort [66, 67].

To this end, participants are exposed to four distinct experimental conditions, each characterized by the same driving events known to induce MS. However, within each of these conditions, participants will undergo varying degrees of sensory synchronization. By comprehensively analyzing the relation between sensory alignment and MS, we aim to offer valuable insights into the enhancement of in-vehicle VR experience for passengers throughout their journey.

3.1 Demographic Information

We recruited 24 participants, 15 males and 9 females, aged between 20 and 41 years (M = 28.1; SD = 4.9) from diverse academic backgrounds including engineering, biology, literature, and business administration and various ethnicities. None of the participants reported any mobility issues that could affect their ability to fully participate. In the participant group, 7 participants had their first experience with VR. Additionally, the data revealed that 11 participants had no previous driving experience. Before starting the experiment, participants were asked to rate their usual degree of car sickness, experienced either in their private vehicles or public transportation, on a five-point Likert scale. The average response indicated a typical MS rating (M = 2.8, SD = 1.1). In appreciation of their time and contribution, each participant received $20 in compensation for their 2-h participation. Our experimental protocol was approved by our research institute.

The data collected from 21 participants were subsequently analyzed. Two participants encountered severe MS during the experiment, specifically when a mismatch between the virtual content and the actual vehicle movement was observed, rendering them unable to continue. Moreover, one participant's data had to be omitted from the analysis due to the loss of data segments caused by interruptions in Bluetooth communication while logging physiological data.

3.2 Apparatus

Our experiment was conducted using a laboratory vehicle, the "Kia Soul EV," specially equipped for this study. This electric vehicle was employed to replicate the experience of using an AV during the experiment. The vehicle was equipped with an alternative voltage power supply in the trunk area. Several additional pieces of hardware were distributed throughout the vehicle, in the rear and front passenger seating area. Figure 2 shows the setup within the vehicle. The details of these equipment are listed below:

- **Processing Unit**: We used an ASUS ROG Zephyrus M16 laptop (12th Gen Intel CoreI i9-12900H, 2.50 GHz, NVIDIA GeForce RTX 3080 Ti) as the main processing unit.
- **VR Headset**: The VR experiences were presented using the Meta Quest 2 headset [61], which supports Unity3D. This headset boasts a resolution of 1,832 × 1,920 for each eye and a refresh rate of up to 90 Hz.
- **Depth Camera**: To enable 3D tracking of participants' hands, we used the Intel RealSense D435 depth camera [62]. An external camera was used to provide an expanded field of view and precise 3D tracking of participants' hands. The camera was placed above the passenger front seat using the vehicle's sun visor.
- **Motorized EMS Generator**: For muscle stimulation, we employed the TENS 7000 unit [63]. To exert control over the EMS generator, each TENS 7000 unit was equipped with two servo motors (HiTEC–HS-5065MG [64]) that were calibrated to operate the EMS channels and control the output intensity. The operation of the servo motors was controlled via an Arduino Nano 33 IoT, with serial communication established between the Arduino board and the Unity 3D to receive operation commands.

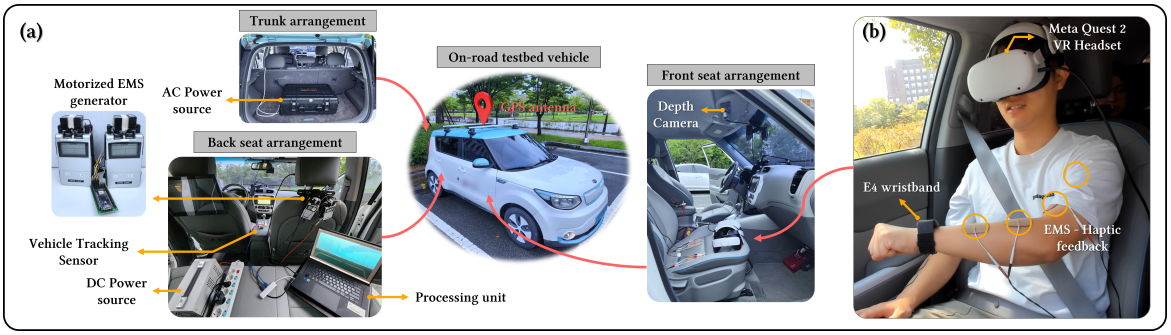

Figure 2: Experiment setup: (a) setup within the vehicle, including electrical supply sources, processing unit, vehicle tracking sensor, depth camera, and Motorized EMS generator, and (b) the equipment and attachments on the participants' bodies, including the Meta Quest 2 headset, E4 wristband, and haptic feedback "EMS" electrodes

- **Vehicle Tracking Sensor**: Our tracking system used a GPS-RTK Dead Reckoning Breakout-ZED-F9R [65] (Qwiic) module by SparkFun, positioned at the vehicle's center. This module received GPS data from an external antenna outside the vehicle and directly measured the inertial measurement unit (IMU) data. The data were transmitted to a laptop via user datagram protocol for use in Unity.
- **E4 Wristband:** To collect physiological data, E4 wristbands [21] were affixed to the participants' left wrists (Figure 2). Bluetooth streaming mode was used to capture blood volume pulse data using a photoplethysmography sensor, which measured variations in blood flow, and to continuously monitor changes in certain electrical properties of the skin via an electrodermal activity (EDA) sensor.

3.3 Experimental Conditions and Interactive Events

We employed a within-group study design, where all participants were exposed to four distinct experimental conditions. We systematically counterbalanced the sequence of conditions such that any potential influence of the order of presentation on the results was evenly distributed and did not bias our findings. Each participant experienced a 600-m on-campus route once per condition at an average speed of 20 km/h (Figure 3). The experiment was controlled in a campus setting with a 30-km/h speed limit.

The total duration of the experiment was 1.5–2 h per participant. Initially, participants were introduced to the experimental procedures, and a 20-min trial session was conducted to familiarize them with the VR interactions and EMS calibration. For the main experiment, we considered four conditions, each comprising a driving session followed by a break of 7 min as a recovery period to mitigate any discomfort and another 15 min for answering questionnaires for subjective assessment. This timeframe was flexible to accommodate individual differences in recovery and questionnaire completion.

To minimize fatigue, each driving session was set to approximately 3 min, in line with prior research [6, 83], that demonstrated the effectiveness of this duration in preventing strong discomfort without compromising the study's validity. This phenomenon was particularly pronounced under some conditions in our experiment,

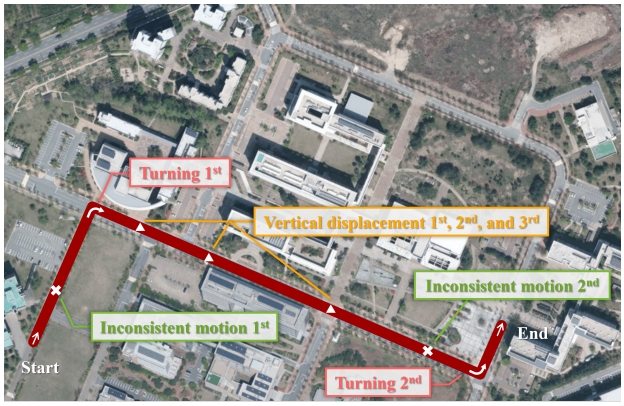

Figure 3: Experimental route, covering 600 m with an average vehicle speed of 20 km/h

such as when participants experienced a misalignment between the visual input in the virtual world and actual car movement, resulting in severe MS. Despite the driving sessions being only 3 minutes long, two participants were unable to complete the experiment because of severe MS symptoms. The driving route was designed to include several MS-inducing events, such as two instances of inconsistent motion, two turns, and three vertical displacements, as illustrated in Figure 3.

Presence and immersion are essential to construct a VE for automotive applications. The sense of presence is crucial for creating realistic and effective simulations and enhanced by immersion. Immersion is defined by the technical aspects of a VE that foster a sense of presence, including high-quality graphics, responsive controls, and multisensory feedback systems [77, 78]. Various immersion levels were integrated across four experimental conditions in our simulation and were thoroughly investigated.

Condition 1 "Baseline–no visual cues" presents a disparity arises between the physical vehicle's movement and the visual input perceived through the HMD. In this condition, we intentionally disabled the vehicle tracking feature, creating an environment where participants perceived a static VR. HMD orientation tracking was enabled, allowing participants to explore the 360° VE freely.

Condition 2 "Visual cues only" involves congruent visual input aligned with the actual vehicle motion, accompanied by engaging auditory stimuli. In *condition 2*, we introduced an environment where the vehicle tracking feature was enabled and integrated with Unity 3D. Then, the virtual submarine, where the participant was situated, was configured to be responsive and synchronized with the actual vehicle movements. This synchronization encompassed the submarine's response to actual vehicle acceleration, deceleration, vertical displacement, and turning. In this setting, participants could navigate through underwater 360° VE and immerse in underwater sound effects (e.g., distant water bubbling) and relaxing music.

Condition 3 "Visual cues and interactions" involves congruent visual input aligned with the actual vehicle motion, augmented by interactive virtual scenarios, and engaging auditory stimuli. In this condition, we ensured the synchronization between the virtual world and the actual vehicle movements as well as the immersive sound effects, similar to *condition 2*. However, an additional layer of engagement was introduced by involving participants in simple interaction scenarios that closely mirrored real-world driving events. These events were strategically incorporated into the VE to create a more engaging experience:

- **Inconsistent motion event** (sudden stops and moves): This event simulated situations wherein the vehicle experiences sudden stops and rapid movements. Two such events were intentionally placed along the predetermined route (Figure 3) that were triggered based on GPS positioning information 20 m before the actual vehicle stop position. When triggered, a large visual wall would gradually descend within the visual scene, indicating that the navigating path of the submarine would soon be obstructed and the vehicle would stop momentarily. Then, participants received visual and auditory cues in the VE to interact with a virtual hammer to destroy this virtual wall. Once the virtual wall was destroyed, a large, animated shark emerged from behind the wall and crossed directly above the virtual submarine. This event was designed to replicate the abrupt movements often experienced during real-world driving, adding a layer of interactivity and excitement to the VR experience. Figure 4 (a) shows the sequence of steps of the inconsistent motion event and participant interaction. Before the vehicle reached the designated stop position, participants initiated motion by moving their right or left arm to grip a virtual hammer to break down the wall. This virtual interaction task aligned with the vehicle's stopping action. The sequence involving the breaking of a virtual wall and animated shark moving toward the submarine was designed to draw participants' attention upward, aligning with the moment when the vehicle started moving again.
- **Turning event**: We incorporated the turning interaction twice along the vehicle route, each for right and left turn experiences (Figure 3). As with the inconsistent motion event, the trigger for the interactive scenario occurred 20 m before the actual turning point. During the training session, participants were instructed to use their left hand to rotate a virtual wheel when prompted to assist the virtual submarine to make a right turn, and conversely, to use their right hand to steer a virtual wheel when assisting the submarine in turning left. Studies have shown that tilting head toward the curve center during turns reduces MS in drivers compared with passengers [16, 17]. Thus, our interactive scenario was designed to encourage participants to adopt this motion. Figure 4 (b) illustrates the steps involved in interacting with the designed scenario during the turning event.
- **Vertical displacement event**: This event was designed to coincide with the vehicle crossing over a speed bump and repeated thrice throughout the vehicle route (Figure 3). The event triggered 20 m before the actual speed bump position, causing a virtual water turbulence effect to appear. A visual and auditory message prompted the participants to grip a virtual handle that appeared in front of them. During this event, participants perceived a vertical displacement in the virtual submarine, and the action of holding onto the virtual bar prepared their bodies for the shaky motion transmitted from the actual route when crossing the speed bump. The sequence of actions for the vertical displacement event is shown in Figure 4 (c). The interactions designed for each driving event were not only aimed at engaging users in specific tasks but also at achieving a synchronization between the participants' bodily responses (informed by proprioceptive feedback) and natural movements induced by the actual vehicle's movement.

Condition 4 "SYNC-VR: visual cues and interactions & EMS" involves congruent visual input synchronized with actual vehicle motion augmented by interactive virtual scenarios, haptic feedback, and engaging auditory stimuli. In condition 4, we maintained the visual alignment between the rendered VR scene and actual vehicle movement, as well as the immersive underwater sound effects, similar to *Conditions 2* and *3*. Additionally, participants encountered the same interactive events described in condition 3. The additional aspect of this condition lies in the incorporation of haptic feedback achieved through a motorized-controlled EMS generator. We used EMS for haptic feedback to simulate the sensation of handling real objects for passengers. EMS induces muscle contractions via peripheral nerve stimulation [70], simulating physical interactions in VR. Although it does not fully mimic all haptic sensations such as the texture or temperature, EMS is particularly adept at creating realistic sensations of muscle engagement and resistance. This capability enhances VR experiences by simulating the physical effort and activity associated with handling real-world objects, making the virtual interaction more dynamic. The EMS signals are triggered when a participant grasps the virtual hammer, steering wheel, or bar. However, proximity to these virtual objects is not sufficient to initiate the haptic feedback, and participants must grasp the virtual objects to experience muscle stimulation. Although this simulation offers a close approximation, it may not fully encapsulate the complete tactile experience of actual object handling. Thus, using EMS aligns with our design goals of delivering tactile sensations and being a tool capable of providing varying levels of feedback to the passengers' arms [15]. The EMS signals targeted the biceps' brachii and flexor carpi radialis muscles of both arms. These muscles were selected to facilitate grip

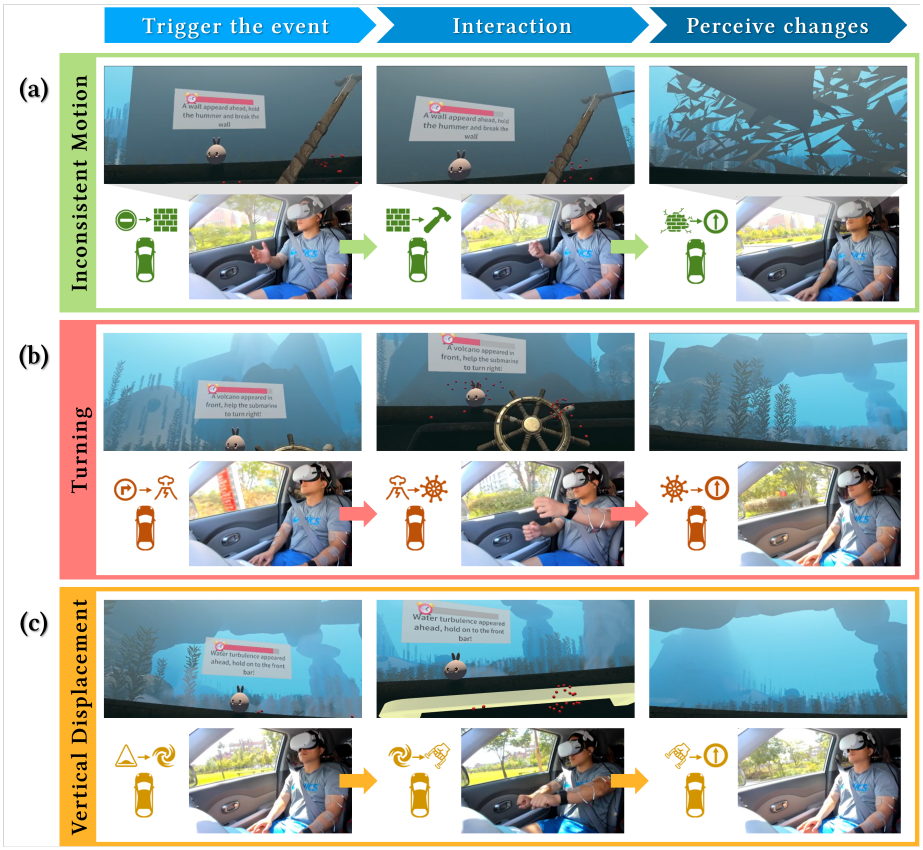

Figure 4: Participant engagement in *conditions 3* and *4* featuring real-world driving events known to induce MS: (a) inconsistent motion, (b) turning, and (c) vertical displacement. An interaction event is initiated by showing visual and auditory notifications, combined with scene changes. Participants then interact with virtual objects, and in condition 4, they also experience haptic cues. These steps are repeated in various forms for the three interaction events.

and manipulate objects as the biceps brachii muscles contribute to elbow flexion and flexor carpi radialis muscles play a role in wrist flexion, both of which are important for such tasks [14]. During the interaction event, stimulation patterns were adjusted to enhance the participants' experience. Both these muscles were stimulated when interactions involved the hammer in an inconsistent motion event and wheel in a turning event. When participants engaged with a virtual bar in a vertical displacement event, only the flexor carpi radialis muscles were stimulated selectively.

In *condition 4*, participants were exposed to both proprioceptive feedback, as observed in *condition 3*, and haptic feedback when engaging with virtual objects. Combining these two distinct forms of sensory input can be collectively referred to as kinesthetic feedback, which encompasses the perception of movement and bodily positioning in response to user actions or external stimuli [44]. It holds significant importance in the realm of VR as it affords users a tangible sense of physical presence and interactive engagement within a digitally simulated environment [45].

3.4 VR Immersive Environment Design

For an enjoyable VR experience in AVs, selecting appropriate content is essential, especially, because in-vehicle VR causes MS and reduces the sense of presence [33, 35]. We designed VR environment as an underwater scene with a submarine setting to alleviate MS and anxiety, thereby creating a comfortable and tranquil ambiance [6]. Underwater scenes are immersive, offering a calming effect with marine life, peaceful landscapes, and vibrant colors. Designing underwater scenes with unique visuals and exploration elements distracts passengers from potential discomfort triggers [82]. In unconventional settings, such as a passenger in a vehicle setting, the submarine theme mirrors real-life experiences, merging virtual and real-life driving. The virtual submarine responds to the vehicle's movements, creating seamless synchronization between the physical and virtual environments, making the experience enjoyable for passengers.

The VR headset used herein features 6 degrees of freedom (6DoF) tracking that uses visual and inertial data to determine the position and rotation of the headset. However, when using 6DoF tracking while driving, the visual and inertial sensors in HMD find it difficult to accurately distinguish between the movements of the vehicle

and the user. Thus, the tracking behavior becomes unpredictable when using a VR headset while driving [10]. Therefore, we switch to the 3DoF tracking mode, which only uses rotation estimation, and install GPS and IMU sensors inside the vehicle to accurately track the vehicle's movement and compensate for changes from the vehicle's rotation on the headset [43]. Furthermore, because of yaw drift of the IMU sensor in the HMD, routine realignments were performed toward the front of the vehicle. As only 3DoF could be used, incorporating hand tracking directly into the headset was not viable. To overcome this challenge and avoid potential conflicts between vehicle movement and headset tracking, depth cameras were used to track users' hand movements in three dimensions. This hand tracking system was developed using the MediaPipe machine learning model [59] and seamlessly integrated it into Unity.

The VR experience was designed to follow a specific route within our institution's campus. During the design process, we calibrated the positions of each event in VR to match with the corresponding events in the real-world environment. For instance, to enhance the user's anticipation of vehicle actions, we incorporated features such as underwater turbulence for vertical displacement events. For turning events, we created an arc of meticulously arranged stones, creating a narrow passageway to clearly indicate upcoming turns. Additionally, we used a virtual wall to simulate the inconsistent motion events. These measures were implemented to provide participants with visual cues to anticipate the real vehicle's upcoming actions.

3.5 Measurements

We collected physiological data along with responses from self-reported questionnaires and qualitative interviews to measure various aspects, including MS, presence, perceived workload, and overall preferences. To evaluate the level of presence experienced by participants, the Igroup presence questionnaire (IPQ) comprising 14 items that collectively assessed overall presence, spatial presence, engagement, and realism was used [23]. The NASA task load index (NASA-TLX) was used to gauge participants' perceived workload in the proposed system [24]. This questionnaire encompasses six subscales designed to derive an overall workload score: mental demand, physical demand, temporal demand, performance satisfaction, effort, and frustration. The simulator sickness questionnaire (SSQ) was used to gauge the induced MS, which employs a 4-point scale (ranging from none = 0 to severe = 3) to assess 16 symptoms categorized into three derived subscales: oculomotor, disorientation, and nausea [22]. Throughout our experiment, the SSQ was administered twice for each condition: prior to initiating VR content (pre-SSQ) and upon concluding the VR content experience (post-SSQ). Furthermore, in the concluding questionnaire administered after participants had experienced all designated conditions, they were asked to rate their overall preferred condition in terms of enjoyment, presence, and general comfort using a 5-point Likert scale.

In terms of physiological measurements, heart rate (HR) and galvanic skin response have demonstrated correlations with MS [18]; therefore, HR was monitored by capturing blood volume pulses using the photoplethysmography sensor embedded in the E4 wristband. The obtained data were then processed using the Kubios HRV scientific software [42] to calculate time domain metrics related to HR variability. The changes in certain electrical properties of the skin were recorded using an EDA sensor inside the E4 wristband. The EDA sensor quantified skin conductance resulting from the activation of the eccrine sweat gland, which is primarily governed by the sympathetic nervous system. Heightened stress levels are characterized by elevated EDA peaks and a high average EDA level [6, 19, 20]. The E4 wristband was positioned on the nondominant wrist of each participant to ensure proper skin contact without impeding blood flow. Data from the E4 device were collected at two distinct times for each condition: prior to engaging with VR content and upon completing the VR content experience. Finally, participants were encouraged to offer their overall impressions of the VR conditions throughout the field interview, emphasizing the distinctions they observed from their own perspectives. This qualitative feedback provided insights into the participants' subjective experiences and preferences, enriching our understanding of the study's outcomes.

3.6 Procedure

Each participant occupied the front passenger seat of the vehicle during the experiment with two experimenters inside the car: one seated in the driver's seat and the other in the rear seat. The first experimenter handled the driving task, provided participants with information about the experiment, managed the logging of physiological data before and during all driving condition, and conducted interviews with participants at the end of all experimental conditions. The second experimenter calibrated the intensity of EMS signals based on the individual sensitivity of each participant, managed the operation of various VR content during each driving condition, and oversaw the collection of subjective data from participants.

At the beginning of the experiment, each participant was asked to fill out a questionnaire for personal information and agreed to data collection. The first experimenter introduced the experiment to each participant and explained the equipment that would be worn and attached to their body. This introduction was followed by calibration procedure to determine the most appropriate EMS signaling for each participant. The calibration procedure determined the minimum and maximum EMS signaling intensities that participants could perceive without any discomfort or pain, which were then assessed during a training interaction session to identify an appropriate signaling level for participants to comfortably engage in the interaction task. During the training session, participants were instructed to grasp and manipulate virtual objects while simultaneously experiencing stimulation in the specified muscles. Participant preferences varied in their choice of minimum or maximum intensity, but the crucial outcome was that all participants found the selected EMS signaling intensity to be acceptable and noted that it contributed to a realistic sense of interaction with virtual objects during the training session.

Before each driving condition, physiological data of participants were recorded using the E4 wristband for 5 min, and their MS levels were assessed using the SSQ questionnaire. Physiological data were recorded immediately before each driving condition and stopped at the end of driving route. Furthermore, participants

completed an online survey that included SSQ, IPQ, and NASA-TLX questionnaires. We repeated this process for each participant until they completed all experimental conditions. At the end, we asked participants to rate each driving scenario on a scale of 1–5 based on their preference. Additionally, participants were invited to share their experiences after trying all conditions and provide suggestions for improving the system.

If participants experienced any MS, we asked them to confirm the dissipation of MS symptoms. They waited until they no longer felt MS before starting the next driving condition. Only two participants experienced severe MS; thus, the experiment was terminated, and their data were excluded from the results.

4 RESULTS

These results present quantitative and qualitative data collected from physiological data, self-reported surveys, and interview responses for each condition. The Empatica E4 data were analyzed using MATLAB [26] and Kubios HRV scientific software [42]. Using Jeffreys's Amazing Statistics Program (JASP) [25], a repeated measures ANOVA test with Bonferroni's *post hoc* analysis and a paired samples t-test was used for self-reported and physiological data to evaluate the impact of MS, the sense of presence, workload, and overall condition preferences when employing VR within a moving vehicle.

4.1 Identifying Self-Reported Data

Presence: Assessing the level of presence was essential for understanding the engagement level with each condition experienced by users in VR. After each condition, participants answered an IPQ questionnaire to evaluate their presence rate. The results show that Sync-VR (*condition 4*) increased the participants' sense of presence when experiencing VR in an AV.

The repeated measures ANOVA test revealed significant differences (F (1, 20) = 19.817, $p < 0.001$, $\eta\ 2 = 0.703$) in user presence among the four conditions, as shown in Figure 5. The results indicate that participants reported significantly higher levels of presence in *condition 4* compared to all other conditions. Additionally, in *condition 3*, the sense of presence significantly increased compared to *conditions 2* and *1*, whereas the sense of presence significantly increased in *condition 2* compared to that in *condition 1*.

Perceived Workload: The overall perceived workload scores were determined by calculating the average scores of the six dimensions within the NASA-TLX questionnaire for the weighted data. Results indicate that the baseline condition (*condition 1*) was associated with the highest perceived workload among all conditions. Participants also reported the lowest mental demand and the highest performance satisfaction when exposed to Sync-VR (condition 4) in contrast to all other VR conditions.

The repeated measures ANOVA test indicated a significant difference in the overall perceived workload (F (3, 60) = 9.950, $p < 0.001$, $\eta\ 2 = 0.332$). A significant increase was observed in the perceived workload in *condition 1* (M = 41.582, SD = 17.393) compared with *condition 2* (M = 25.878, SD = 12.518, $p < 0.001$), *condition 3* (M = 28.159, SD = 10.551, $p = 0.002$), and *condition 4* (M = 23.413, SD = 9.044, $p < 0.001$). No significant differences were observed between *conditions 2, 3*, and *4*.

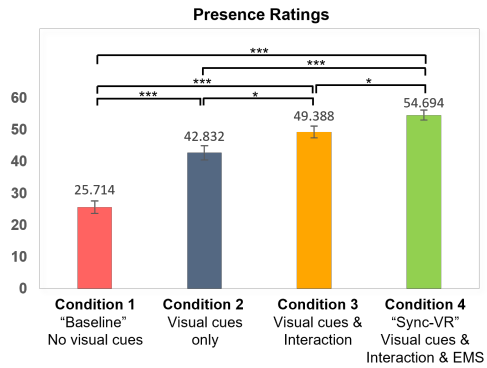

Figure 5: Presence rating across the four conditions; significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$

The repeated measures ANOVA test indicated a significant difference in the overall perceived workload (F (3, 60) = 9.950, $p < 0.001$, $\eta\ 2 = 0.332$). The perceived workload significantly increased under *condition 1* (M = 41.582, SD = 17.393) than that under *condition 2* (M = 25.878, SD = 12.518, $p < 0.001$), *condition 3* (M = 28.159, SD = 10.551, $p = 0.002$), and *condition 4* (M = 23.413, SD = 9.044, $p < 0.001$). There was no significant difference among *conditions 2, 3, and 4*.

To assess the disparity in participant ratings for each dimension in the NASA-TLX questionnaire under different conditions, we analyzed the six dimensions separately (Figure 6). The results revealed a significant difference in the overall perceived mental workload (F (3, 60) = 13.219, $p < 0.001$, $\eta\ 2 = 0.398$), performance satisfaction (F (3, 60) = 27.349, $p < 0.001$, $\eta\ 2 = 0.578$), and frustration (F (3, 60) = 11.393, $p < 0.001$, $\eta\ 2 = 0.363$) between the four conditions.

Motion Sickness: To quantify the level of induced MS experienced by users after using VR in each condition, SSQ was conducted twice for each condition: prior to exposing the user to VR content (pre-SSQ) and immediately after exposing them to VR content (post-SSQ). Participants reported high levels of MS when exposed to *conditions 1* and *2*. However, their MS symptoms slightly decreased after experiencing Sync-VR (*condition 4*).

The paired t-test for the mean total score indicated a significant increase in the induced MS in both *condition 1* (t (20) = −4.452, $p < 0.001$) and *condition 2* (t (20) = −2.633, $p = 0.016$). In contrast, in *conditions 3* and *4*, the results demonstrated no significant differences in the induced MS after experiencing *condition 3* (t (20) = −0.484, $p = 0.634$) and *condition 4* (t (20) = 0.260, $p = 0.797$), respectively. When considering only the mean value of rated MS before and after participants engaged with VR in condition 4, MS decreased after participants engaged with the VR content from (M =16.96, SD = 23.39) to (M = 15.17, SD = 33.864), as shown in Figure 7. To ensure consistency in MS levels across participants before initiating each experimental condition, the pre-SSQ scores for each condition were assessed. The ANOVA test indicated no significant variations in the MS levels across participants before starting experiment (F (3, 60) = 0.169, $p = 0.917$). This observation underscores the homogeneity

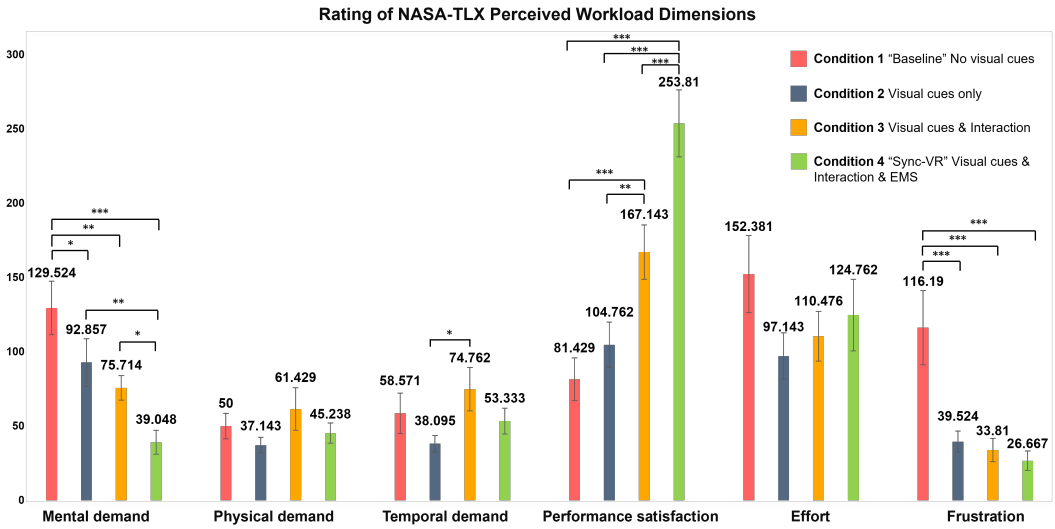

Figure 6: Perceived workload (NASA-TlX) for each dimension across the four conditions; significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$

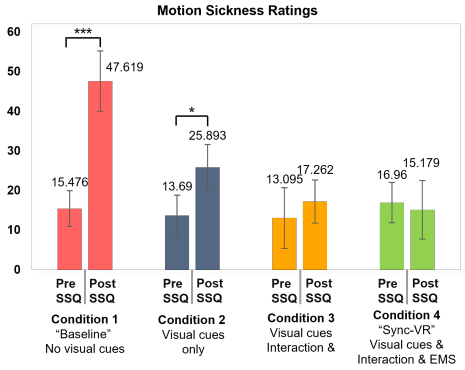

Figure 7: MS rating across the four conditions (before and after each condition); significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$

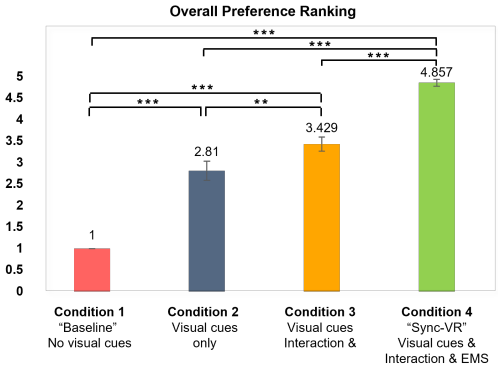

Figure 8: Overall preference ranking across the four conditions; significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$

in participants' MS experiences at the outset of each experimental scenario.

To understand the patterns revealed by the MS questionnaire, its three distinct subscales were examined, namely oculomotor, disorientation, and nausea [22], before and after each condition. The SSQ subscale scores indicated that the predominant symptom in MS was oculomotor, followed by nausea and disorientation. In *condition 1*, the paired t-test showed a significant difference in the subjective experiences related to oculomotor (t (20) = −3.639, p < 0.001), disorientation (t (20) = −3.972, p < 0.001), and nausea (t (20) = −4.787, p < 0.001) sensations before and after the experiment. Interestingly, significant differences were also observed in the oculomotor (t (20) = −2.050, p = 0.027) and nausea (t (20) = −2.000, p = 0.030) subscales in *condition 2*. However, in *conditions* 3 and *4*, no significant differences were found in the examined subscales.

Overall Preference Ranking: Participants rated their overall preferences on a scale from 1 (very low) to 5 (very high) after completing all four conditions. They preferred and found Sync-VR (*condition* 4) to be the most comfortable option when experiencing VR, followed by *conditions 3* and *2*. Conversely, the baseline (*condition 1*) was neither preferred nor comfortable for participants.

The ANOVA test results revealed a significant difference in the overall preference rates (F (3, 60) = 105.574, p < 0.001, $\eta 2$ = 0.841), as shown in Figure 8. *Condition 4* (M = 4.857, SD = 0.359) received the highest preference rating, followed by *condition 3* (M = 3.429, SD = 0.746), *condition 2* (M = 2.810, SD = 1.030), and *condition 1* (M = 1.000, SD = 0.0).

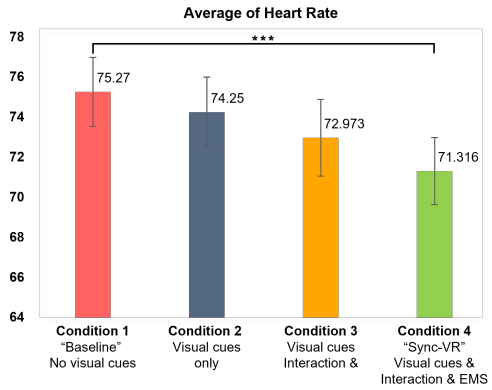

Figure 9: Average HR across the four conditions. Significance levels are indicated as $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

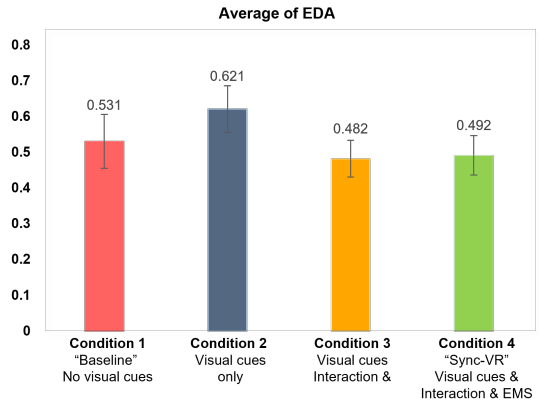

Figure 10: Normalized EDA (Tonic) data across the four conditions

4.2 Identifying Physiological Measurements

Heart Rate: HR was used to understand the induced MS from each condition. Consistent with the subjective responses, Sync-VR (*condition 4*) was found to be the most comfortable option, and it did not induce MS or stress compared to the baseline condition (*condition 1*).

The repeated measures ANOVA test revealed that the overall measured HR (beats per minute) across all conditions was statistically significantly different (F (3, 60) = 3.328, $p < 0.035$), as shown in Figure 9. The mean HR in *condition 1* (M = 75.27, SD = 7.904) was significantly higher than that in *condition 4* (M = 71.316, SD = 7.66, $p < 0.02$).

Electrodermal activity: In the data postprocessing procedure for EDA, a series of systematic steps were followed to ensure accurate analysis. First, the tonic data were extracted from the raw EDA recordings collected before and during each experimental condition. Then, the average tonic component was computed for the preconditions across all participants, establishing a baseline for comparison. The difference between the EDA tonic component data recorded during the experimental conditions and the corresponding precondition baseline for each participant was calculated. Then, the resultant difference in tonic component data for each participant was normalized, and the average values for the normalized tonic component was derived for all participants for each specific condition.

The statistical analysis of the EDA did not reveal any significant differences (F (3, 60.696) = 0.898, p = 0.448, $\eta 2$ = 0.045), as shown in Figure 10.

5 DISCUSSION

Herein, we determine the effect of synchronizing the senses while using VR in a moving vehicle on improving travel experience. These findings will be used to answer our research questions.

5.1 Subjective Responses

5.1.1 Presence and Sensory Alignment. Presence, often described as the "feeling of being there" in a VE, plays a pivotal role in shaping the overall experience of VR content in a moving vehicle. In the baseline condition (*condition 1)*, where a disparity existed between real and virtual motion, participants reported the lowest level of presence (Figure 5). This suggests that when VE becomes static and unresponsive to the actual vehicle movement, users feel less present in the VR world, aligning with findings from prior research [6]. When visual cues were synchronized with the actual motion of the vehicle and auditory cues were present in *condition 2*, participants experienced significantly higher levels of presence compared to *condition 1* [10]. In *condition 3*, the visual alignment was retained with the actual vehicle motion and auditory cues were incorporated, as in *condition 2*. However, interactive scenarios that simulate real-world driving events were additionally introduced. Participants reported a significant increase in the sense of presence in *condition 3* compared with that in *conditions 1* and *2*, indicating that interactive scenarios can contribute to enhancing the sense of presence to some extent [38, 39]. In SYNC-VR (*condition 4)*, which also maintained visual match with the vehicle movement and auditory cues, participants encountered the same interactive scenarios as in *condition 3* wherein haptic feedback was added using an EMS device. Participants reported the highest levels of presence among all conditions, significantly surpassing *conditions 1*, *2*, and *3*. This indicates that haptic feedback, combined with other synchronized sensory inputs, substantially enhances the feeling of being present in the VE. This finding aligns with previous studies demonstrating that the use of multisensory interaction contributes to increased presence and provides enhanced VR experiences [40, 41].

Thus, a static VR scene or visual digital content that does not synchronize with the vehicle's movements provides the lowest sense of presence. In contrast, aligning visual cues with the actual vehicle's motion along with auditory cues considerably improves the feeling of presence for passengers using VR in a moving vehicle. Conditions wherein visual and other sensory inputs match, particularly when integrated with auditory cues, interactive scenarios that provide proprioceptive feedback, and haptic cues as in *condition 4*, the highest levels of presence are experienced. This highlights the critical role of synchronized sensory inputs in enhancing passengers' presence level when using VR in a moving vehicle.

5.1.2 In-Vehicle Perceived Workload. The analysis of the NASA-TLX questionnaire provides valuable insights into the perceived workload experienced by participants across the four experimental conditions (Figure 6). This multidimensional assessment offers a comprehensive view of the cognitive demands imposed by each VR scenario within the moving vehicle. *Condition 1* yielded the highest overall perceived workload, and participants reported significantly higher levels of frustration and mental workload. Furthermore, participants rated *condition 1* significantly lower in terms of performance compared to the other conditions. This outcome is consistent with expectations, as the lack of congruence between the VE and real-world motion likely required greater cognitive effort to process. This finding aligns with a previous study that explored the relation between VR immersion and mental workload, demonstrating that a decrease in presence is linked to higher mental load [47]. The data from *conditions 2, 3*, and *4*, where various levels of sensory alignment were introduced, consistently showed lower overall perceived workloads compared to *condition 1*. Notably, frustration and perceived mental workload progressively decreased from *conditions 2* to *4*. In *condition 4*, participants reported the lowest significant levels of mental workload and frustration level compared to all other conditions. Additionally, participants rated *condition 4* the highest in terms of performance. In terms of physical workload and effort, participants did not report any significant differences between the four conditions.

These results highlight the positive impact of aligning sensory cues, including visual, auditory, proprioceptive, and haptic feedback with actual vehicle motion in reducing mental workload and frustration while enhancing performance during VR experiences in a moving vehicle. Sync-VR (*condition 4*), which incorporated these elements, was deemed the most effective in terms of perceived workload and performance.

5.1.3 Assessing Motion Sickness. SSQ scores indicate that MS significantly increased in *conditions 1* and *2*, as shown in Figure 7. In *condition 1*, a discrepancy between visual and vehicle motion cues was present, a known inducer of MS. In *condition 2*, the reduced level of presence experienced by participants also contributed to this effect. In contrast, the introduction of sensory alignment in *conditions 3* and *4* noticeably impacted MS. Participants reported no significant differences in induced MS after experiencing *conditions 3* and *4*, as indicated by the p-values. Furthermore, the mean values of rated MS before and after participants engaged with VR content in *condition 4* indicated a slight decrease in MS, suggesting that the sensory alignment strategies employed in *condition 4* may have a mitigating effect on MS.

These results underscore the potential of sensory alignment, particularly in *conditions 3* and *4*, to reduce the adverse effects of MS when using VR in a moving vehicle. This aligns with the goal of making in-vehicle VR experiences more comfortable for passengers.

5.1.4 VR Condition Preferences. The results of the overall preference rankings shed light on the participants' subjective evaluations of different experimental conditions. These rankings offer valuable perspectives on which condition passengers found most enjoyable and comfortable during their VR experiences in a moving vehicle.

Figure 8 shows that *condition 4*, which implicates the highest level of synchronization of sensory inputs, significantly enhances the overall passenger experience. The highest preference ranking for *condition 4* indicates that passengers experienced reduced MS and enjoyed a heightened sense of presence. *Condition 3*, although did not reach the preference levels of *condition 4*, demonstrated a superior and significant appeal compared to *conditions 1* and *2*. This implies that the incorporation of interactive tasks, which offer participants proprioceptive feedback, and the synchronization of visual cues with vehicle motion coupled with auditory cues significantly contribute to an enriched VR experience. Notably, the absence of haptic feedback in this condition does not hinder its capacity to enhance the overall user satisfaction. *Condition 2*, characterized by the synchronization of visual cues with vehicle movement and auditory cues but without interactive tasks or haptic feedback, garnered a preference ranking lower than *condition 3*. However, *condition 2* was significantly preferred than *condition 1*. This suggests that aligning visual cues with vehicle motion and immersing participants in auditory cues creates a more enjoyable experience than a static VR setting. *Condition 1* received the lowest preference ranking, which underscores the importance of sensory alignment in creating an enjoyable and comfortable VR experience within a moving vehicle.

5.2 Physiological Responses to Sensory Alignment

Herein, the physiological responses are assessed to elucidate the influence of sensory alignment on the HR and skin conductance of participants. This analysis will help determine the experimental factors impacting the physiological aspects of the participants, thereby shedding light on the intricate relationship between sensory alignment and human physiology.

5.2.1 Heart Rate. The analysis of HR provided valuable insights into the physiological responses of participants across different conditions (Figure 9). The higher HR in *condition 1* suggests that participants experienced increased physiological arousal and potential discomfort due to the incongruence between visual input and the motion of the vehicle. This finding aligns with our expectations, as a mismatch between visual and kinesthetic sensations can induce MS, leading to increased HR as the body responds to this discomfort. Interestingly, in *condition 4*, where sensory inputs were synchronized by aligning visual, auditory, proprioceptive, and haptic cues, a significantly lower mean HR was observed than *condition 1*. Thus, aligning sensory inputs had a stabilizing effect on participants' HRs. The reduced HR in *condition 4* suggests that participants experienced less physiological stress and MS, possibly because their sensory inputs were better matched to the actual vehicle movements. By synchronizing the sensory inputs of participants, we observed a reduction in mean HR. This trend is particularly evident in *conditions 2, 3*, and *4*.

5.2.2 Skin Conductance. Figure 10 shows that no significant differences existed in the EDA data (tonic component) among any of the experimental conditions, which aligned with results of a similar study [6]. However, a slight decrease was observed in the 'tonic component of average EDA for *conditions 3* and *4* compared to *conditions 1* and *2*.

Significant differences were not observed in the EDA data due to several factors. First, the experiment was conducted on a short route, and changes in the tonic EDA component often require a longer time to manifest [68]. Second, a temperature-controlled environment was maintained during the experiment, which may have influenced EDA readings. Moreover, the proximity of the EMS electrode to the EDA sensor electrode in *condition 4* could have had an impact on the EDA readings [69]. Overall, while we expected to see clear effects of sensory input alignment on participants' skin conductance data, our experimental setup may not have been conducive to capturing these effects.

5.3 Qualitative Interviews

This section highlights the valuable feedback provided by the participants during the interviews conducted after each participant experienced all four conditions. To reference specific participants, the notation, P_n, is used, where n represents the number of participants (1–24).

All participants experienced varying levels of MS when they were involved in *condition 1*. P_4's commented on this discomfort, "*I feel the need to vomit whenever the car proceeds through a turn.*" Similarly, P_8's experience was intensely negative, as they rated their MS a "*9 out of 10*," highlighting the severity of their discomfort. P_{23} also echoed these sentiments, emphasizing the intensity of MS during turning events, describing it as "*strong*."

Participants' responses suggested a noticeable improvement in managing MS in condition 2. P_8 stated that "It is relatively better than condition 1. I think the visual match helps me feel less MS, but I still feel dizzy when the vehicle stops or accelerates." Thus, condition 2 reduces MS intensity but does not completely mitigate it. Furthermore, P_{14} reflected on condition 2, highlighting the impact of the VE on their MS experience, and stated "Here, there is not much to do; I am just observing the virtual 3D scene. Then, I paid more attention to the discrepancy between the virtual and the actual world. Therefore, my feeling of MS was higher during this session." This comment underscores the influence of the nature of VR content on the MS experienced by participants.

However, the majority of participants commented on a decrease in their MS feelings as they progressed to *conditions 3* and *4*. Most of the participants, excluding P_5, P_{20}, and P_{24}, expressed that *condition 4* provided them with the highest level of presence in the VR experience. They reported a sense of control and noted a lack of MS compared to the other conditions. P_6 shared, "*I definitely will select the one with feedback over my muscles when interacting with virtual objects; it is more fun and feels more involving.*" P_7 on the absence of MS said "*I can rate the MS level as zero in this case*" and elaborated that "*Including EMS in this condition makes me feel more immersed; I can certainly feel that I am grabbing something. In general, I think I was less connected to the outside environment when having EMS signals applied to my body.*" P_{11} offered insights, stating that "*It was a surprise for me to not feel MS when crossing over a speed bump or when turning. I think being involved in work helped a lot to avoid the feeling of MS during those moments.*" Similarly, P_{14} reflected on their experience and stated that "*I think I get a lower feeling of MS because I was fully immersed in the virtual world to the point where I just forgot the entire outer world.*" P_{23} also provided positive feedback: "*It was very good to experience resistive forces when interacting in a virtual world; it increased my immersive feeling.*" Additionally, *conditions 3* and *4* were compared. P_{16} stated that "*Having cues about the expected upcoming motion of the vehicle helps me to feel a sense of control over the vehicle's movement. Such a design makes me feel more comfortable and safer. Meanwhile, having the EMS signal applied to my arms when interacting made me more engaged with the VE.*" P_7 also compared the two, saying, "*These two conditions were the most preferred by me. In the case of a short trip, I may select condition 4, and for a long trip, I prefer condition 3.*" This feedback collectively highlights the importance of immersive elements and feedback mechanisms in enhancing virtual experiences and mitigating MS.

Conversely, P_5, P_{20}, and P_{24} found *condition 2* to be the most comfortable for relaxation during VR use in a moving vehicle. However, they unanimously favored *condition 4* for its entertainment and excitement value. Note that P_5, P_{20}, and P_{24} did not experience MS in *conditions 2*, *3*, and *4*, with the exception of *condition 1*. This lack in MS likely influenced their wide range of preferences when selecting the most suitable VR content. They found *conditions 2*, *3*, and *4* to be viable options depending on their specific preferences and goals for using VR in a moving vehicle.

5.4 Addressing Research Questions and Insights on In-Vehicle Adaptive VR

To extrapolate the findings of our study, we use the outcomes derived from the triangulation of data from three sources: subjective responses, physiological measurements, and qualitative interviews. This comprehensive approach allows us to seek answers to the research questions posed herein.

RQ1: Does an exclusive reliance on visual cues adequately enhance presence and mitigate MS across a range of real-world driving events that trigger the most MS? We found that relying solely on visual cues in *condition 2* increased the sense of presence and reduced MS. This conclusion was supported by subjective measures, including the IPQ, NASA-TLX, and SSQ questionnaire, which showed positive responses to the visual matching condition. In addition, physiological data, particularly HR, exhibited a decreasing trend in the visual matching condition, indicating reduced physiological stress. However, visual cues, particularly when synchronized with real vehicle movements, showed a positive enhancement. This was particularly noticeable when compared to the condition where the virtual scene does not respond to the vehicle movement in *condition 1*. Some participants still experienced MS and reported it during interviews. Furthermore, the visual matching-only condition did not yield the highest scores for the sense of presence or lowest scores for MS. Other conditions, where multiple sensory inputs were synchronized, showed potential for improving comfort levels in VR within a moving vehicle. These conditions resulted in increased overall presence and decreased MS, as evidenced by a significant decrease in the average HRs. Therefore, exclusive reliance on visual cues alone is insufficient to adequately enhance presence and mitigate MS across a range of real-world driving events that trigger MS.

RQ2: How do various sensory inputs, including proprioceptive feedback, visual cues, auditory cues, and haptic cues, interact to influence presence and MS in in-vehicle VR experiences? Our results show that enriching VE with multisensory inputs enhances the feeling of presence, but only when these inputs are synchronously integrated, considering the effect of the external environment (vehicle movement) on the passenger body. Generally, including additional sensory inputs does not consistently guarantee an increase in presence [80]. Therefore, enriching VE by adding extra sensory inputs can enhance presence, provided that it keeps users connected to the main task without causing distractions [81]. In a moving vehicle, generating multimodal sensory inputs is difficult because of the human perceptual sensitivity to spatiotemporal misalignments across modalities. Thus, the SYNC-VR framework is designed to align various sensory inputs with the actual vehicle motion in VR. Our results confirm that increasing the number of sensory inputs from *condition 1* to *condition 4* improves the level of presence. Therefore, we recommend using visual, auditory, and haptic cues along with tailored interactive scenarios to generate proprioceptive feedback in response to anticipated vehicle motion.

Participants under *condition 3*, where visual and auditory cues were combined with interactions, experienced no remarkable difference in MS levels before and after the driving condition. Proprioceptive feedback induced by interactive scenarios play a significant role in controlling MS, particularly in the absence of haptic feedback. Under *condition 4*, where only haptic cues were added to the mix of *condition 3*, no significant change was observed in MS levels before and after the driving condition. Because haptic feedback isolated from the interactive scenario in *condition 4* was not provided, its role in mitigating MS could not be ascertained. However, the inclusion of haptic feedback in *condition 4* significantly enhanced the sense of presence. These results are consistent with those of previous studies [44, 45]. Under *condition 4*, participants experienced proprioceptive and haptic feedback, which are collectively referred to as kinesthetic feedback. This encompasses the perception of movement and body positioning in response to user actions or external stimuli. Kinesthetic feedback plays a role in VR environments as it affords users a tangible sense of physical presence and interactive engagement in a virtual setting. This supports our findings regarding the influence of haptic feedback on presence enhancement. These results show that relying solely on visual cues is insufficient for controlling MS or enhancing the sense of presence in VR settings in a moving vehicle.

RQ3: How does the anticipation of on-road driving events, such as turns, vertical displacement, and irregular accelerations, influence the need for real-time adaptive tuning of VR experience to improve passenger presence and decrease MS during AV travel? During interviews, several participants highlighted the importance of cues that allow them to anticipate upcoming driving events. These cues provided passengers with a sense of control over the vehicle's movements, enhancing their overall experience. This insight underscores the significance of keeping passengers informed about the actual actions of the vehicle when using VR, particularly in the context of AVs. Maintaining this connection and anticipating upcoming actions fosters trust and comfort in passengers [60]. Therefore, it is imperative to establish a framework that adaptively tunes VR content to synchronize with the vehicle's actions in real-time. This framework should prioritize sensory alignment, as demonstrated herein. Thus, we propose a real-time framework aimed at synchronizing passenger sensory experiences while using VR in AVs. The focus on AVs is driven by their capability to provide data on upcoming events well in advance. We build on the work conducted by McGill's (PassengXR) [43] and integrate advanced predictive analytics into VR. PassengXR adeptly aligns VR content visually with real-time vehicle movements, whereas our proposed system uniquely incorporates predetermined interaction scenarios based on the vehicle's location. This predictive strategy, substantiated by the results, shows enhanced sense of presence and reduced MS. It not only aligns virtual experiences with vehicle dynamics but also provides prospective and haptic feedback, bridging the gap between virtual and physical realms. Furthermore, we focus on identifying the optimal synchronized sensory inputs to mitigate MS during anticipated driving events (inconsistent motion, turning, and vertical displacement) [33, 36]. Figure 11 describes the proposed framework, which includes the components implemented herein and those that will be integrated in future studies. This framework represents a promising approach for enhancing passenger comfort and reducing MS when using VR in AVs.

5.5 SYNC-VR: Safety, Social Dynamics, and Broadening Applications

The utilization of VR in manual or semiautonomous driving has raised safety concerns [71]. However, these concerns are substantially reduced in the context of fully AVs. The key to this improvement is the absence of driver intervention requirement in fully autonomous systems, reducing the risks of delayed reactions linked to VR usage [73]. Our SYNC-VR framework has been designed for passenger use, particularly for integration in these more advanced vehicular systems. As the era of fully AVs emerges, the application of SYNC-VR within these vehicles becomes increasingly advantageous. Results underscore the important role of sensory synchronization in enhancing passenger comfort. SYNC-VR prioritizes safety, alleviates MS, and enhances the sense of presence, thereby becoming a pivotal framework in vehicular mobility that can be widely adopted.

SYNC-VR can be adopted for other in-car VR applications, such as entertainment, education, and productivity scenarios (e.g., attending a work meeting, working on a design, or editing a document). Each application requires customized SYNC-VR modifications to synchronize the sensory experiences of users with vehicle movements. For instance, in applications, such as movie watching or document editing, the primary application window can be placed centrally within a virtual scene surrounded by a 3D VE [72]. Within the 3D VE, various components of the SYNC-VR framework can be integrated. This starts with visual cues informing the passenger about the vehicle's anticipated movements, accompanied by interactive tasks that provide proprioceptive feedback in response to the anticipated vehicle's motion. Additionally, embedding EMS as a haptic cue adds realism to these interactive tasks. Previous studies have reported the effectiveness of combining visual cues and haptic sensations to mitigate MS when using VR [51, 52]. Thus,

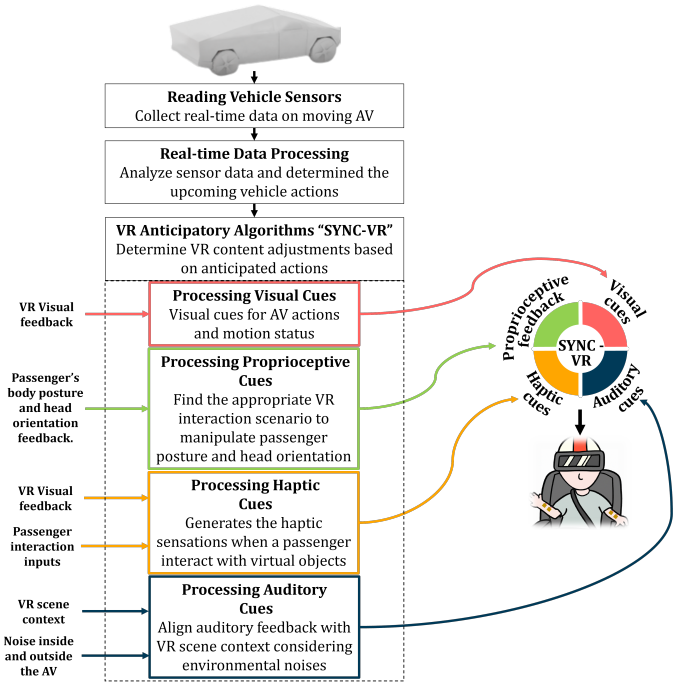

Figure 11: Adaptive VR system in AVs

we incorporated proprioceptive feedback as a crucial additional element for controlling MS during VR use in vehicles. Therefore, there is a need to determine the limits for applying all components of the SYNC-VR framework, while maintaining the passenger's focus on the primary application. One consideration is to blend visual cues of vehicle motion and interactive content into the primary application window (e.g., inside the movie window) to prevent distraction from the primary task. Initially, the SYNC-VR framework was tested using virtual content designed for entertainment and relaxation, such as 3D underwater scenes. In our future studies, we will explore the integration of the SYNC-VR framework into a wide range of applications while maintaining passenger engagement as the primary application. Our foremost priorities are to sustain passengers' sense of presence and minimize MS sensation.

6 CONCLUSION, LIMITATIONS, AND FUTURE WORK

In this study, we synchronized different passenger sensory inputs during VR usage in an on-road vehicle to provide insights into the use of VR in moving vehicles and its impact on passenger experience. Although visual cues alone increased the sense of presence, they were not sufficient for mitigating MS across various driving dynamics. Proprioceptive feedback was the most effective sensory input for controlling MS, while the added haptic cues greatly improved the sense of presence. Furthermore, a multimodal sensory approach, rather than one relying only on visual cues, increased the overall sense of presence and decreased MS, especially in driving events that induce MS, such as inconsistent motions, turns, and vertical displacements. The results were validated using triangulation across three methods: subjective assessments, physiological measures, and qualitative interviews. This study's implications include guidelines for developing adaptive VR content that can be integrated into AVs. This involves aligning sensory inputs with the anticipated real-time vehicle movements and engaging passengers with interactive VR scenarios, thereby offering an immersive experience to them without causing discomfort.

During our experiment, which was conducted on a short route, all participants have similar rest postures. However, passenger body postures can vary considerably during long trips. To address this, we plan to design experiments with long trip durations, utilizing intelligent soft sensor structures and deep learning models to monitor posture and design better interactions. This study focused on evaluating participants' sense of presence and MS while using VR in complete isolation from the real environment using the HMD. Therefore, tests were conducted in a nonautonomous vehicle with predetermined driving events to validate the significance of synchronizing sensory inputs. In the future, however, we will integrate autonomous driving features for real-time data collection and assess the performance of SYNC-VR framework in response to anticipated maneuvers. The long-term potential of SYNC-VR framework beyond entertainment must be explored. In the future study, the incorporation of SYNC-VR into different VR applications (e.g., gaming, conducting a remote meeting, editing documents, and watching media) must be considered to maximize its benefits while ensuring user engagement and safety. Our ultimate goal is to establish SYNC-VR as an integrated system in future AVs.

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